# QUESTS

**IN PURSUING OUR QUESTS, WE WILL FULFILL THE INNATE HUMAN DESIRE TO UNDERSTAND OUR PLACE IN THE UNIVERSE, AND BUILD THE FOUNDATION FOR TOMORROW'S BREAKTHROUGH TECHNOLOGIES. EACH QUEST HAS ASSOCIATED RESEARCH DESTINATIONS AND QUESTIONS, AND POTENTIAL FOR SOCIETAL BENEFITS.**

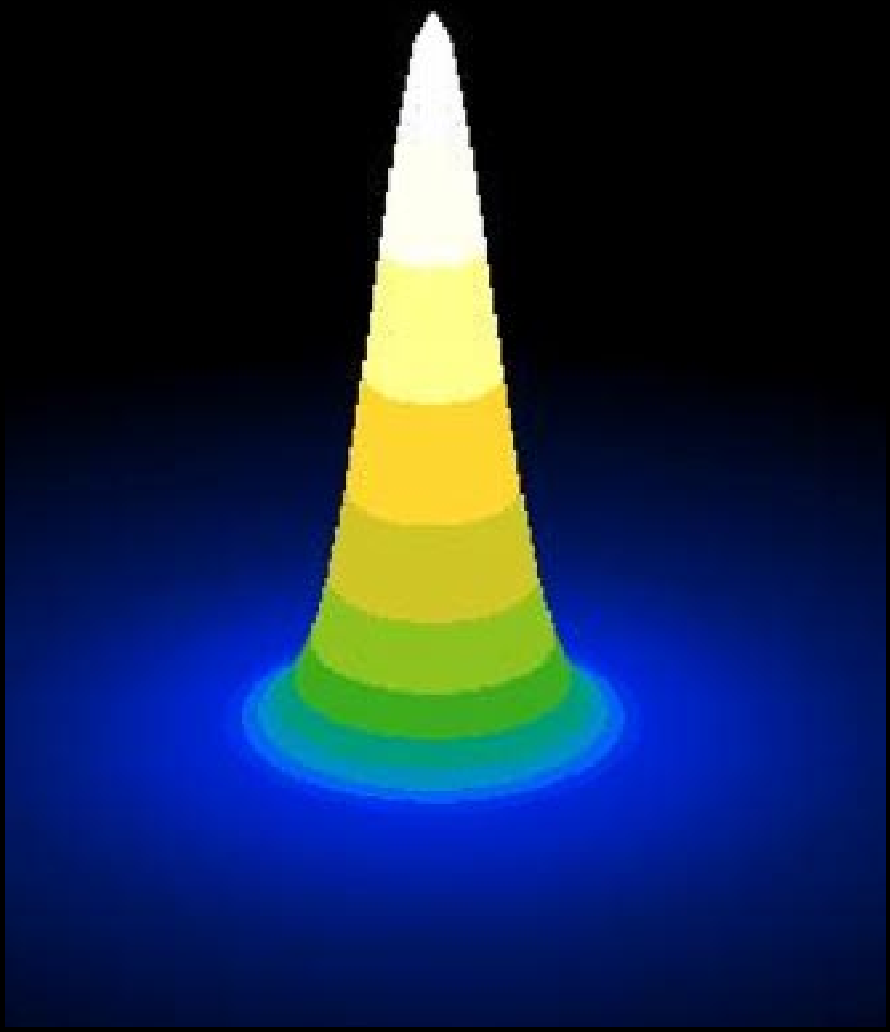
1. *To discover and explore fundamental physical laws governing matter, space, and time.*

2. *To discover and understand organizing principles of nature from which structure and complexity emerge.*

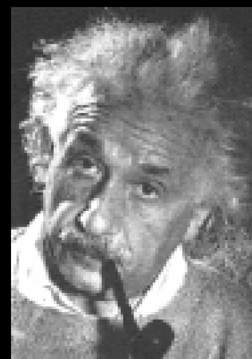
# QUEST

1

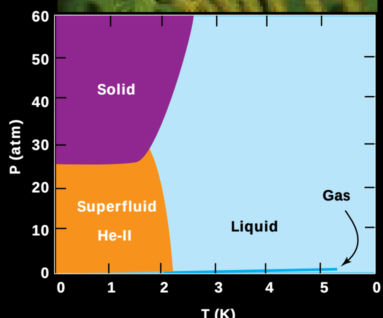
To discover and explore fundamental physical laws governing matter, space, and time.



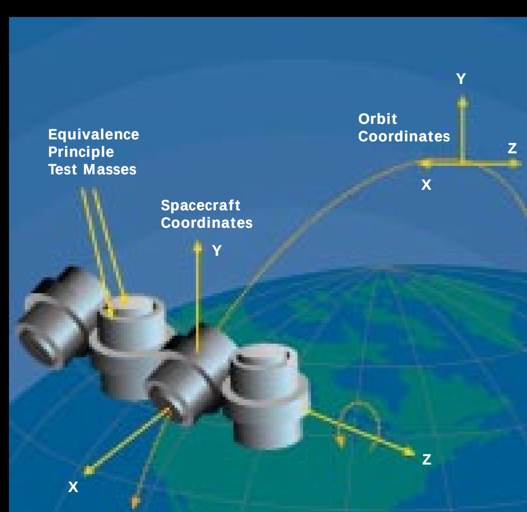
▲ *When cooled to ultralow temperatures, many atoms condense into the Bose–Einstein condensation state. By studying this phenomenon in microgravity, we can understand more about the microscopic world of atoms.*



*We will explore Einstein's general relativity theory, using Gravity Probe-B to measure how the rotating Earth drags space–time.*




*What is the relationship between fundamental laws and the evolution of the physical world into the rich diversity we observe? Important clues can be found in space-based studies of critical phase transitions.*




*In the search for new fundamental forces and symmetries and development of a unified theory, the Satellite Test of the Equivalence Principle (STEP) can study whether all bodies fall with the same acceleration or if there are additional unknown forces.*

# QUEST 1

## To discover and explore fundamental physical laws governing matter, space, and time.

*“There are grounds for cautious optimism that we may now be near the end of the search for the ultimate laws of nature.” —Stephen Hawking*

Today’s cosmological models seem to capture many of the principal features of the universe and the laws that govern them. Knowledge of the four fundamental forces — gravity, electromagnetism, and the strong and weak nuclear forces — and their interactions with particles places humanity on the verge of understanding matter, space, and time more completely as one system. Experiments that look deeply into the smallest and largest pieces of the universe will help prove and improve current theories, placing scientists ever closer to the identification of a unified order that influences the whole fabric of space–time and everything within it.

Arriving at such a grand unified theory depends on finding critical confirmations or new discoveries that will act as signposts, telling us whether our theories are on the right track. For Quest 1, this program will address the following signposts, or “research destinations,” to test the validity of theories in phenomena that occur throughout the universe at all scales. These important research destinations are:

***1) To explore the range and validity of Einstein’s theory of general relativity.***

Einstein’s theory says that space and time depend on the reference frame of the viewer. What this means is that the universe is not still and unchanging, but that the beginning, development, and end of the universe all depend heavily on the content of matter, its motion, and the observer’s motion. This theory raises some important questions to be answered, such as:

- Does general relativity apply throughout the universe from subatomic to astronomic scales?
- How does matter in motion and rotation “drag” space–time?
- What is the nature of black holes, and what can we learn about how these rapidly moving, extremely dense phenomena affect the fabric of space–time?
- What can gravitational waves (as yet undiscovered waves predicted by the theory of general relativity) tell us about black holes and the early universe right after the Big Bang?

***2) To understand the nature of the quantum world.***

The quantum world is a realm in which the inner workings of the smallest systems will provide clues to the most basic building blocks of nature and their influence on larger scales. We want to pursue answers to such questions as:

- What can macroscopic quantum systems (e.g., neutron stars and clouds of laser-cooled atoms) tell us about the subatomic world of the nucleus and how its elementary parts work?
- How can we manipulate and employ quantum systems like atoms to develop practical devices?
- How can quantum theory be reconciled with the theory of gravitation when the two theories seem to be so different?

***3) To search for new fundamental forces and symmetries that support the development of a unified theory.***

Such a theory will describe in one overarching framework all the fundamental forces (including any that haven't yet been discovered) and the relationships among elementary particles. To do this, scientists must rigorously examine the following mysteries:

- Do all bodies fall at the same rate? Do different kinds of clocks keep the same time?
- Are nature's "constants" really constant?
- How can the theory of gravitation be reconciled with quantum theory?
- What lies beyond the Standard Model, the theory that describes three of the known four forces?
- Are there any weakly coupled, short-range, or long-range forces to be discovered?

***4) To understand the relationship between fundamental laws and the evolution of the physical world.***

We observe the world to be far more complex in its organization than the laws that guide it. The whole secret of how the universe looks the way it does depends on understanding how uniform systems change under external influences, producing variations that reorganize into recognizable patterns. We wonder:

- What is the relationship between broken symmetries and the complexity of nature that emerges as a result?
- Can we understand nature through renormalization group theory, which attempts to describe the behavior of systems interacting at vastly different lengths and scales?

- How do the simple rules in fundamental theories apply to complex systems? How do initial conditions determine the way in which complex systems are ultimately organized?

### Societal Benefits

Historical benefits from physics research studying fundamental physical laws include:

- Lasers for cutting, surgery, scanners, holograms, information storage, etc.
- The Global Positioning System
- The World Wide Web
- Particle-beam cancer therapy
- Gamma-ray imaging for treaty verification and medical use
- An enlightened view of the universe in which we live

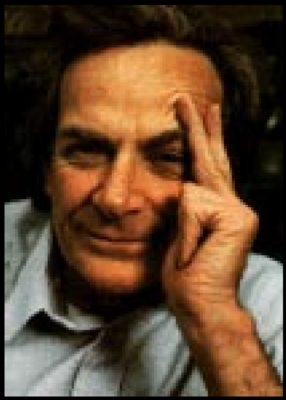
Projected benefits from microgravity physics research on fundamental laws include:

- New advanced technologies and instrumentation
  - — Space lasers and power transmission
  - — Ultraprecise clocks and more accurate navigation systems
  - — Improved competitiveness of U.S. industry
- Technology breakthroughs resulting from scientific discovery
  - — Atom interferometer and atom laser
  - — Harnessing the quantum world for revolutionary computing advances
- Enlighten humanity's view of the universe in which we live
  - — Inspire young minds to excel
  - — Motivate a new generation to expand scientific frontiers

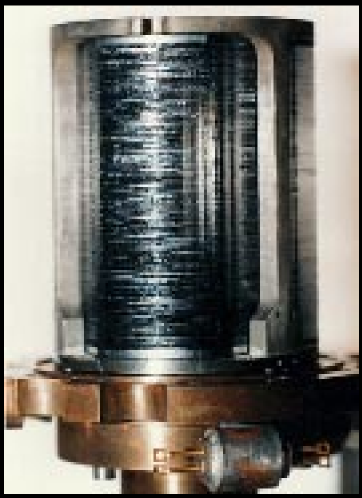
# QUEST

## 2

To discover and understand organizing principles of nature from which structure and complexity emerge.



*"The vastness of the heavens stretches my imagination. ...Far more marvelous is the truth than any artists of the past imagined!"*
*— Richard Feynman*



*The Confined Helium Experiment, which flew on Space Shuttle Columbia in 1997, measured the effects of finite size on the heat capacity of helium in space.*

◀ *Studying how broken symmetries give rise to patterns will yield clues to the role of symmetry in nature's structure and complexity. This photo of "frost heaving" shows how the internal action of frost changes an overlying surface as subsurface ice forms.*

◀ *The diversity and complexity of nature emerge from basic laws. Space-based experiments on critical transitions will test the validity of current theory that seeks to explain the behavior of highly complex systems.*

# QUEST 2

## To discover and understand organizing principles of nature from which structure and complexity emerge.

*"Nature uses only the longest threads to weave her patterns, so each small piece of her fabric reveals the organization of the entire tapestry." —Richard Feynman*

Snowflakes, honeycombs, spider webs, and spiral galaxies — everywhere we look, at every scale, we see a universe rich in emergent pattern. Far from being random and formless or perfectly rigid in shape and style, the universe is alive with symmetrical patterns that aren't quite perfect. Studying nature's symmetries and how they break (change in pattern) will reveal some of the rules that determine natural processes. Just as a perfectly symmetrical pond can be broken into rings by a stone's throw, the more perfect symmetry of the early universe was broken by infinitesimal changes that produced all the diversity we observe today. By understanding how such changes occur, we can predict how nature will behave. This understanding can help us to develop products that improve human lives. It may also help to unite our fundamental theories about the universe. Already, a recognition of symmetry between the electromagnetic and weak forces has united theories describing them, and the search continues for uniting all four forces. By pursuing the following research destinations, we shall contribute to an understanding of the patterns that rule atoms, the universe, and life within it.

***1) To study matter under ideal and unique experimental conditions in order to uncover underlying organizing principles.***

Studying a fluid on Earth is difficult because the weight at the top of the sample presses down on the liquid at the bottom, making the fluid denser at the bottom. A low-gravity environment makes a sample uniform, allowing scientists to measure more precisely what happens when an ultrapure system such as liquid helium passes into a superfluid state. Understanding such transitions in matter, especially at the critical point where there is no distinction between two phases, depends on knowing:

- What are the effects of finite size on the properties of matter?
- How do nonequilibrium conditions modify properties of matter?
- Under what conditions is the renormalization group concept valid?
- What can complex fluids teach us about organizing principles?

***2) To determine the role of symmetry in establishing structure and complexity in nature.***

Fluids naturally have a convective flow on Earth, where the lighter fluid goes to the top and the heavier to the bottom. Patterns form as a given fluid rises and falls, but it is not predictable under what conditions (velocities) patterns will form. When the fluid starts out, it is uniform; when the pattern emerges, we see a break in symmetry. By studying the way patterns form (self-organize), we will seek answers to these questions:

- What is the role of symmetry in establishing self-organized critical behavior?
- How does broken symmetry give rise to complex patterns?
- What is the role of symmetry in establishing chaotic behavior?

***3) To study macroscopic quantum phenomena in order to determine how laws in the quantum world manifest at normal length and time scales.***

Condensed helium and cold alkali atoms are unique testbeds displaying quantum effects even in large macroscopic systems. When we cool atoms so that they condense into one quantum state (so that they're at the same lowest-energy state), a single wave function describes their motions. Phonons (density waves going through atoms) and vortices (whirlpools of moving atoms) are excitations known to exist in this state. Well-posed studies of these macroscopic quantum systems in a low-gravity environment can answer important open questions such as:

- What role do quantized vortices play in the superfluid helium transition?
- How can we use macroscopic quantum effects for practical devices?
- What are the ultimate limits of matter-wave devices such as atom lasers and interferometers?

***4) To establish how rich diversity emerges from basic laws.***

Calculations based on renormalization group (RG) theory are thought to explain the behavior of many highly complex systems. The validity of the RG approach can best be tested by space experiments on critical transitions. We would like to know:

- Does RG theory correctly identify universal and nonuniversal properties of complex systems?
- Can this theory be applied to other complex systems, such as weather patterns?

## Societal Benefits

Historical benefits from physics research studying fundamental physical laws include:

- Microprocessors and computers
- Magnetic data storage
- Compact disc players
- Cryogenic technology for industrial processes
- Magnetic resonance imaging
- Superconductor applications
- An enlightened view of the universe in which we live

Projected benefits from microgravity physics research on fundamental physical laws include:

- New advanced technologies and instrumentation
  - — Magnetostrictive actuators for precise manipulation of mechanical devices
  - — High-resolution thermometers, pressure gauges, and magnetometers
  - — Improved competitiveness of U.S. industry
- Technology breakthroughs resulting from scientific discovery
  - — Computer technology enabled by understanding finite-size effect
  - — Harnessing the quantum world
- An enlightened view of the universe in which we live
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